A Look-Up-Table Approach to Inverting Remotely Sensed Ocean Color Data

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LONG-TERM GOALS

Remote sensing algorithms for the marine environment have traditionally relied upon semi-empirical approaches to determining water column properties. These algorithms are usually depth-integrals of a proxy of desired information, i.e., chlorophyll algorithms are a proxy for water column autotrophic biomass. The goal of this work is to use the increased spectral resolution of current satellite and aircraft data systems to solve for the depth-dependent optical properties of interest, e.g., absorption and scattering, as well as the depth-dependent distribution of the individual optical constituents, e.g., diatoms, dinoflagellates, cyanobacteria, CDOM, and sediment. This will be accomplished ?create a large dataset of simulated remote sensing reflectance, R_{rs}, using a radiative transfer model and developing a look-up-table approach to R_{rs} inversion.

OBJECTIVES

1) Help develop the code to quickly run $>10^7$ calculations of R_{rs}.

2) Provide IOPs for individual optical constituents and establish their depth-dependent profiles for simulations.

3) Help develop search optimization schemes to invert satellite and aircraft R_{rs} to depth-dependent optical properties and constituent profiles.

APPROACH

Various ocean color remote sensing instruments are now available or under development. These sensors all measure spectral upwelling radiances which, after atmospheric correction, give the spectral water-leaving radiance $L_w(\lambda)$ or an equivalent remote-sensing reflectance $R_{rs}(\lambda)$; here λ is the wavelength. The end goal of ocean color remote sensing is to extract from L_w or R_{rs} useful environmental information such as the absorption and scattering properties of seawater constituents (phytoplankton, dissolved substances, mineral particles, etc), chlorophyll concentration, or bottom bathymetry and bottom type in shallow waters. Currently available algorithms for extracting environmental information generally use empirically derived correlations between the quantity of interest and the ratio of L_w or R_{rs} at two wavelengths. For example, the algorithm for extracting chlorophyll concentrations from SeaWiFS data is based on the ratio R_{rs}(490 nm)/R_{rs}(555 nm)

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14. ABSTRACT

Remote sensing algorithms for the marine environment have traditionally relied upon semi-empirical approaches to determining water column properties. These algorithms are usually depth-integrals of a proxy of desired information, i.e., chlorophyll algorithms are a proxy for water column autotrophic biomass. The goal of this work is to use the increased spectral resolution of current satellite and aircraft data systems to solve for the depth-dependent optical properties of interest, e.g., absorption and scattering, as well as the depth-dependent distribution of the individual optical constituents, e.g., diatoms, dinoflagellates, cyanobacteria, CDOM, and sediment. This will be accomplished ?create a large dataset of simulated remote sensing reflectance, Rrs, using a radiative transfer model and developing a look-up-table approach to Rrs inversion.

15. SUBJECT TERMS

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(algorithm OC2 in O'Reilly et al., 1998). Such ratio algorithms do not make full use of the available spectral data even in the SeaWiFS sensor, nor can they be expected to provide much information about water composition (as opposed to just total absorption or total chlorophyll concentration). Ratio algorithms provide erroneous results if applied to waters outside the range of the empirical data from which they were derived. For example, the OC2 chlorophyll algorithm, which was derived for Case 1 waters, will provide incorrect chlorophyll values if applied to Case 2 waters containing mineral particles or high levels of CDOM (Colored Dissolved Organic Matter).

The Hydrolight radiative transfer numerical model (Mobley, 1994) gives an exact solution of the in-water radiative transfer equation given the water inherent optical properties (IOPs, namely the absorption and scattering properties of the water body), the incident sky radiance, and the bottom depth and reflectance (bottom BRDF). The water IOPs can be built up from any number of components, such as various microbes, dissolved substances, organic detritus, mineral particles, or microbubbles. For remote-sensing purposes, the relevant Hydrolight output is the spectral water-leaving radiance. We will first construct a database containing a large number of Hydrolight runs corresponding to different combinations of water composition (different microbial, dissolved, or mineral substances at different concentrations), sky conditions (different solar angles and atmospheric conditions), sensor viewing directions, wavelengths, and so on. The resulting water-leaving radiances in the database, L_{wd}, are in principle all different. Given a measured water-leaving radiance L_{wm} (obtained from atmospheric correction of an at-sensor radiance), one can then "look up" the L_{wd} spectrum that most closely matches L_{wm}. The water IOPs and bottom conditions in the actual water body are then taken to be the values that were used in Hydrolight to generate the selected L_{wd}. We thus effect an inversion of the measured spectral signature by the conceptually simple process of spectrum matching and then looking up the answer in the database.

The work is part of a larger project led by C. Mobley of Sequoia Scientific, Inc. (N0001400D01610001)

WORK COMPLETED

The HYDROLIGHT v4.1 software package that contains the numerical solution to the RTE using invariant imbedding techniques includes over 60 Fortran program units, as well as a supplementary Graphical User Interface, IOP sub-models, and supplementary data files. The implementation of this software over large spatial and temporal domains is cumbersome within a reasonable amount of time. Thus, the core of the numerical invariant imbedding solution has been re-written and condensed into a single Fortran 90 subroutine (excluding 3 subroutines containing general mathematical algorithms that are freely available from the NETLIB library). Input variables to the subroutine are the depth-dependent total absorption, particulate scattering, and scatter phase function, as well as the total geometric depth, solar zenith angle, cloud fraction, and spectral incident downwelling direct and diffuse irradiances. Output are data files containing the surface emergent polar flux (L_w), the specularly reflected radiance at the surface, and the in- water irradiance fields (upwelling/downwelling, scalar/planar) at 1.0 meter increments from just beneath the surface to the bottom.

The quadrature discretization technique as described by (Mobley, 1994) is maintained at 20 theta (polar) quads and 24 phi (azimuthal) quads, yielding a 10 degree angular resolution in the polar and 15 degree resolution in the azimuth. Reducing this resolution can increase the computational speed. However, for this first step we maintain the full quad resolution so that no information regarding the angular distribution of the light field immediately above and below the air/sea interface is “smeared out". This is particularly crucial when considering the interaction between the solar zenith and azimuth angles and the local sea surface realized transmittance and reflectance functions, as they become less accurate with decreased quad resolution.

A large increase in computational efficiency was achieved by only solving the invariant imbedding solution to the RTE for the first mode of the Fourier polynomial analysis. Briefly, the HYDROLIGHT 4.1 RTE solution radiance amplitudes in each quad have a Fourier polynomial with 12 modes. Each upward integration of the Riccati differential equations that solve for the standard operators (transmittances and reflectances) of the radiance amplitudes must be repeated 13 times for both the sine and cosine modes of the Fourier polynomial, resulting in a total of 26 integrations in the upward sweep for a single depth of interest. Unfortunately, for a complete solution to radiances in all quads there can be no truncation of this series. Fortunately, to solve only for irradiances as well as the radiance values of the "polar caps" only the first Fourier component, $l = 0$, need be considered. Since all sine mode amplitudes are zero for $l = 0$, we reduce 26 integrations of the "upward sweep" to only one. This is possible because the first Fourier component of the radiance amplitude has no azimuthal dependence, and so quantities that also have little azimuthal dependence – irradiances and polar radiance – can be computed only from the first Fourier component. It is important to emphasize here that the full azimuthal quad resolution was maintained (n=24) only to address the complexities of the air/sea interface. This is because "when the upper boundary is involved, the amplitude for one *l*-mode is directly coupled to the amplitudes for all other *l*-modes" (p. 407, Mobley, 1994). Accordingly, we describe the reflectance and transmittance of radiance through the air/sea interface for all quads and *l* -modes. Once through the air/sea interface, however, the *l*-modes are de-coupled, allowing us to ignore the remaining *l*-modes when integrating the Riccati differential equations at depths of interest.

RESULTS

Given the same depth dependent IOP's, surface boundary condition, bottom boundary condition (reflectance), and using the same discretized phase function for particle scattering, our results from OPTIMv1 match those of HYDROLIGHT v4.1 quite well, as shown in Figure 1. These validation runs were for a depth of 20 meters, output at every meter, and a spectral resolution of 5 nm from 400 to 700 nm, yielding 60 wavebands. Results from all depths and wavebands are shown in Figure 1. Examination of Figure 1 reveals that there is a very slight underestimation of L_w and E_u by OPTIMv1 when compared to HL. This may be due to the scattering of radiance from lower quads into the polar cap that is accounted for only by the full HL solution. The computational reduction between the full HL solution and OPTIMv1 can be seen in Figure 2. Greater computation reductions may be possible through any reduction in depth resolution, spectral resolution, and quad resolution. However, we currently prefer to maintain this resolution for comparisons to other programs. At an average computation time of one waveband every two seconds this data base can grow to over 15 million R_{rs} values in a year's time using a single Intel PIII processor. We expect significant decreases in processor computational time when the code is transported to the NRL Origin 3800. In addition, the Origin 3800 is a massively parallel machine that will also greatly reduce the wall clock computation time through simultaneous calculations on >100 processors.

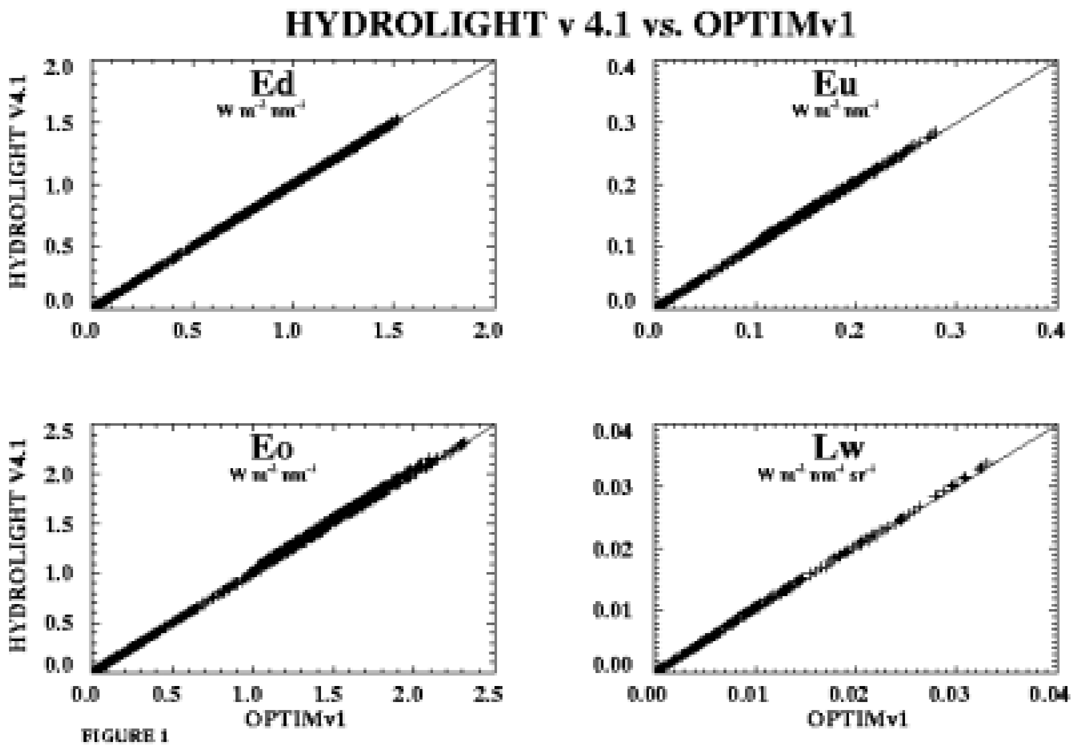

Figure 1. Comparison of Hydrolight 4.1 and OPTIM 1 results for the same IOP data set and downwelling irradiance field.

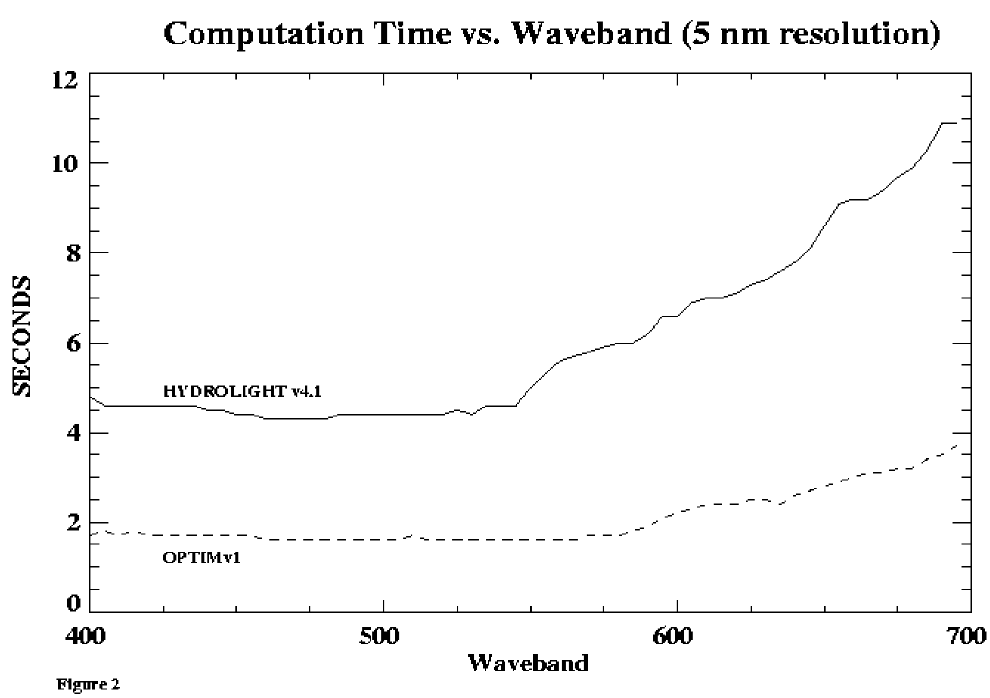

Figure 2. Reduction in computational speed for OPTIMv1 versus Hydrolight 4.1.

IMPACT/APPLICATIONS

Full utilization of the hyperspectral data field from aircraft and satellite data streams will provide the mechanism to invert R_{rs} to depth-dependent optical properties such as absorption, scattering, and bathymetry. These are critical data streams for performance prediction modeling, as well as initialization and validation of predictive optical simulations. This program will provide the tools necessary to rapidly invert R_{rs} data to depth-dependent optical properties.

RELATED PROJECTS

The work is part of a larger proposal being led by C. Mobley of Sequoia Scientific, Inc. (N0001400D01610001), in coordination with the hyperspectral remote sensing program of C. Davis, Code 7212, Naval Research Laboratory.

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